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MIX DESIGN FOR SELF-COMPACTING CONCRETE

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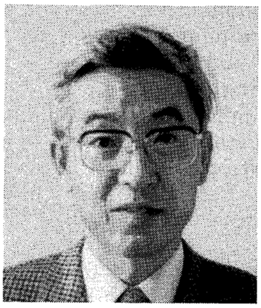

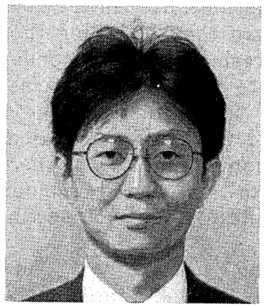

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Self-compacting concrete requiring no consolidation works in site has been developed in Japan to improve the reliability of concrete and concrete structures. This paper describes the role of constituent materials on the self-compactability of fresh concrete and a mix design of self-compacting concrete.

Keywords: self-compacting concrete, mix design, free water

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1. INTRODUCTION

It has been eight years since the authors advocated the development of self-compacting concrete (then called "consolidation-free concrete") in February, 1986[1] and over five years since the first prototype of such concrete was developed in August 1988[2]. The authors have continued fundamental work and application studies, and recently published some of the results[3]. The number of structures using this type of concrete has been increasing from year to year, and there is growing anticipation of its effectiveness. Among the difficulties in making self-compacting concrete more widespread, this paper takes up the issue of mix design, which is the most important subject in the fundamental study of this type of concrete, and reports on the current situation and future areas of study.

In this paper the authors use the term "self-compacting concrete" to refer to this type of concrete, because they consider that the most prominent feature of the concrete is its ability, when fresh, to fill all corners of formwork under its own weight. We feel it is more appropriate to refer to this as "self-compacting", a term implying a more active capability, than "consolidation-free". The terms "high-flowability" and "superflowable" are coming into use, but they do not clearly indicate that the fresh concrete fills the form nor that consolidation is unnecessary. In addition, they do not distinguish it form "flowing concrete" as used in Europe and America. For these reasons, the authors have adopted the new term "self-compacting".

"High-performance concrete" is the term the authors have used to refer to concrete that not only possesses self-compactability, but also exhibits excellent performance while green and after hardening[4]. It has become misleading, however, to use this term in the sense of concrete with self-compactability, because the same term has been used in recent years in a sense in Europe and America[5]. Consequently, the authors use "self-compacting high-performance concrete" to refer to the concrete they advocate, and "self-compacting" to refer to its capabilities while it is fresh[6] (see Fig. 1).

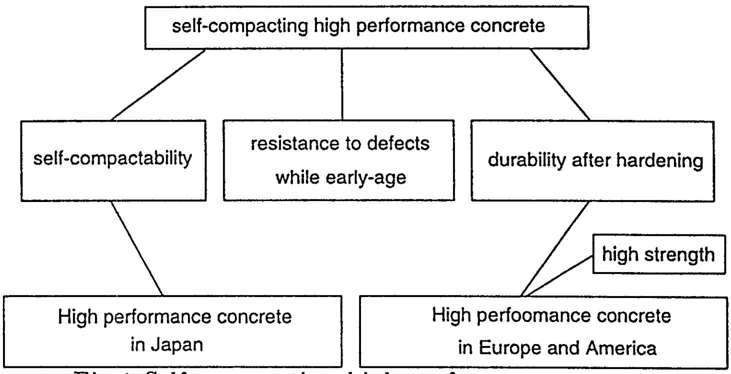

Fig.1 Self-compacting high performance concrete

2. METHODS OF REALIZING SELF-COMPACTABILITY

2.1 Adding a viscosity agent

Fresh concrete is susceptible to segregation, because it is a composite material consisting of ingredients with different sizes and specific gravities. Since the risk of segregation increases as the deformability increases, there is generally a trade off between high deformability and high resistance to segregation. The reason why the stiffest workable consistency has conventionally been recommended is that it avoids the risk of segregation at the sacrifice of deformability. Concrete for molding at factories can only be proportioned to be superstiff on the premise that powerful vibratory consolidation is to be carried out.

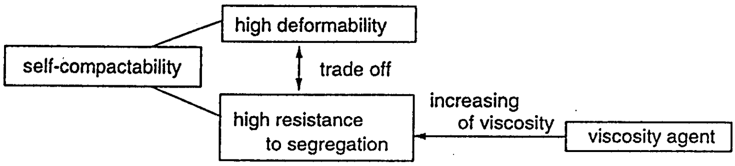

Fig.2 Improvement of self-compactability with a viscosity agent

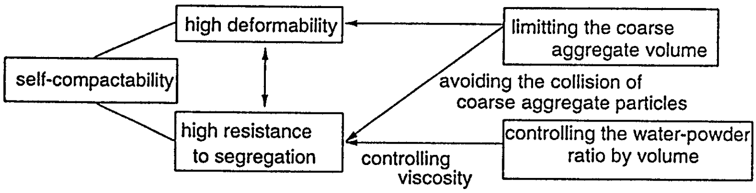

Fig.3 Realizing self-compactability with controlling mix proportion

Self-compacting concrete realizes high deformability while avoiding the risk of segregation. The increased viscosity of the paste is effective in inhibiting segregation (see Fig. 2). Antiwashout underwater concrete is a kind of self-compacting concrete placed underwater; segregation is strictly inhibited by the addition of a large quantity of a viscosity agent, thus preventing the cement particles from dissolving into the water. It is therefore not suitable for reinforced concrete structures in air; the viscosity is so high that entrapped air may not be released and the concrete may not easily pass through spaces congested with steel such as reinforcing bars. Self-compacting concrete with a viscosity agent is an antiwashout concrete with reduced viscosity suitable for use in air.

Takeshita et al realized self-compacting concrete for the first time by this method, and attempted to apply it to actual structures[7]. The balance between the viscosity agent and the superplasticizer is important for increasing self-compactability. However, there is a limit to how much self-compactability can be increased only by this method. It is a method the authors adopted but abandoned in the process of development.

2.2 Limiting the coarse aggregate volume while controlling the water-powder ratio by volume

This is a method in which the volume of coarse aggregate is limited so as to inhibit the collision of coarse aggregate particles near obstacles, while the water-powder ratio by volume is adjusted to approximately 1.0 to impart an adequate viscosity to the paste and thus avoid segregation. This is the method the authors used for the prototype self-compacting high-performance concrete[2] (see Fig. 3).

In this method the powder content is higher than in conventional concrete, due to the increased paste content. This increased cement content may cause defects in certain types of structures. Consequently, part of the powder is substituted by such mineral admixtures as fly ash and ground granulated blast furnace slag, or limestone powder. This is the type of self-compacting concrete used for the anchorages of the Akashi Kaikyo Bridge connecting Honshu and Shikoku Islands. Its powder content is increased by using a large amount of limestone powder[8] (see Fig. 4). This is the first case of a self-compacting concrete in which the maximum aggregate size was 40 mm.

		W/C (%)	s/a (%)	weight of material per unit volume of concrete (kg/m³)					
				W	C	LF	S	G	Ad
standard concrete		55.8	36	145	260	30	650	1253	3.9
self-compacting concrete	1A	55.8	45	145	260	150	769	965	6.355
	4A	55.8	36	145	260	150	609	1121	7.8

C:low-heat type cement with fly ash and blast-furnace slag
LF:limestone powder
Ad:superplasticizer

Fig.4 Self-compacting concrete used for the anchorage of the Akashi Kaikyo Bridge

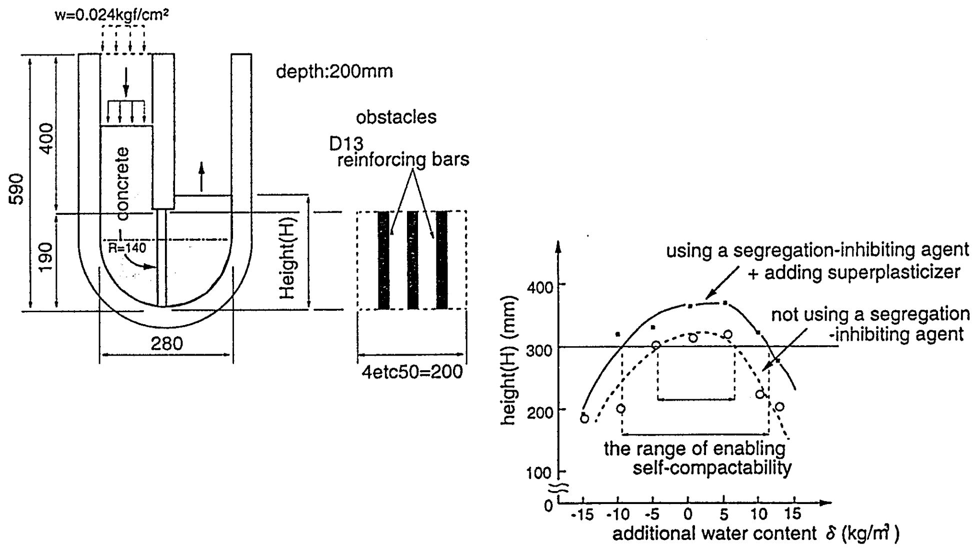

Fig.5 Improvement of self-compactability using a segregation-inhibiting agent

Shindo and Matsuoka et al developed a method of increasing the degree of self-compactability easily by adding a segregation-inhibiting agent, which is a polymer insoluble in water, to the prototype self-compacting high-performance concrete[9] (see Fig. 5). This high level of self-compactability has now become attainable by suitably designing such proportions as the volumetric water-powder ratio, without using any segregation-inhibiting agent.

Whereas a superplasticizer is essential with either method, it is also important to suitably proportion the aggregate content and impart suitable deformability and viscosity an the paste. The frequency of collision and contact between aggregate particles increases as the relative distance between the particles decreases. Therefore, the internal stress increases when concrete is deformed, particularly near obstacles. It has been revealed that the energy needed for flowing is consumed by this increased internal stress, so blockages occur[10] (see Fig. 6). Limiting the coarse aggregate content, whose energy consumption is particularly intense, to a level lower than in normal proportions is effective in avoiding such blockages.

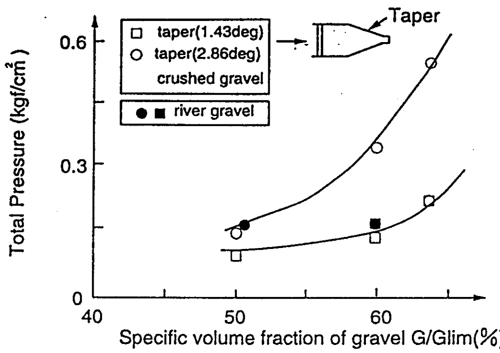

Fig.6 Total pressure at the inlet of tapered pipe with respect to the gravel content

In order to increase the deformability of the paste, the volumetric water-powder ratio should be increased, or a superplasticizer should be added. In order to impart viscosity, the volumetric water-powder ratio should be reduced, or a viscosity agent should be added. Imparting deformability means reducing the energy consumed internally or by friction on the boundary. Conversely, imparting viscosity means increasing the energy required for deformation. Thus there is a clear trade off between deformability and viscosity. If viscosity is to be increased by reducing the volumetric water-powder ratio, there is no choice but to use a superplasticizer to achieve greater deformability. If there was a range where deformability and viscosity are balanced, self-compactability could be realized without the help of a viscosity agent. Fortunately, the addition of a superplasticizer was found to cause little loss of viscosity, while it greatly improves deformability. Thus it was found that there is a range where high viscosity and good deformability coexist in a balanced manner.

It is necessary to impart viscosity an the paste because paste with high viscosity inhibits the settlement of coarse aggregate particles, which have a higher specific gravity than the other ingredients, and thereby maintains the uniformity of the concrete; when the concrete is deformed, paste with high viscosity does not suffer localized increases in internal stress due to the approach of coarse aggregate particles with large grain diameters. In this regard it is important to regard concrete as having both liquid and solid properties, because it is a composite of particles of various sizes and specific gravities.

3. LEVEL OF SELF-COMPACTABILITY

Whether or not self-compactability is realized depends not only on the properties of the concrete, but also on the placing conditions, as well as the boundary conditions as determined by the obstacles, such as steel present in the formwork. It is therefore possible to select a methodology in which the degree of self-compactability of concrete is altered depending on the placing conditions and thestructure being constructed, while a high level of quality control is maintained as in conventional concreting. From the standpoint of production control, however, greater reliability is attainable if a single type of concrete is produced rather than various types, since the properties of fresh concrete are more sensitive to changes in material quality and proportion than those of hardened concrete. A change in the quality of the ingredients or the production process leads to a lower level of self-compactability in most cases. Choosing a high degree of self-compactability has become relatively easy; it is normally easier than to maintain a high level of quality control.

At present, the authors recommend a method in which the self-compactability is set at a high level, while the tolerances are adjusted depending on the structure in question. It is difficult to maintain self-compactability at a specific level; more difficult, in fact, than controlling the quality of conventional concrete. Failure to achieve the specified self-compactability can impair the reliability of the entire structure. It is safer to set a high level of self-compactability even when a lower level is adequate, and then adapt to various conditions of the structure and construction by permitting a wider variability production, thereby widening the control limits.

4. EFFECTS OF MATERIALS ON SELF-COMPACTABILITY

4.1 Powder materials

Selection of the powder is important, because its properties not only greatly affect self-compactability but also govern the quality of the hardened concrete. The powder is the smallest solid particle present in the concrete. Some the water in fresh concrete is confined by solid particles, and one of the characteristic features of powder is that a unit volume of particles confines a large amount of water. Flow tests on paste show a linear relationship between the flow area and the volumetric water-powder ratio. The volumetric water-powder ratio at which the paste ceases to deform can therefore be extrapolated (see Fig. 7). If this point is defined as the amount of water confined by the powder, as a ratio this value always falls in the range 0.7 to 1.0, though there is a slight scatter depending on grading, shape, and such properties as reactivity (see Fig. 8). In other words, powder confines an amount of water approximately equivalent to its own volume.

There is an optimum volumetric water powder ratio for imparting on the paste a viscosity suitable for self-compacting concrete, and this value is closely related to the ratio of water confined by the powder. The ratio of water confined by well-shaped powders, such as fly ash, is extremely small, and so their optimum water-powder ratios by volume are also small. The degree of early hydration and grain size distribution also affect the ratio of confined water; the ratio of water confined by moderate-heat portland cement is generally lower than that of ordinary portland cement.

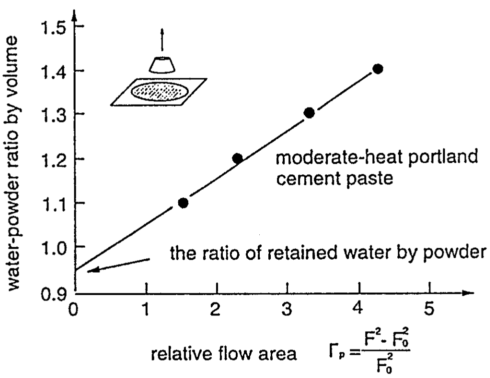

Fig.7 Relationship between the relative flow area and water-powder ratio by volume

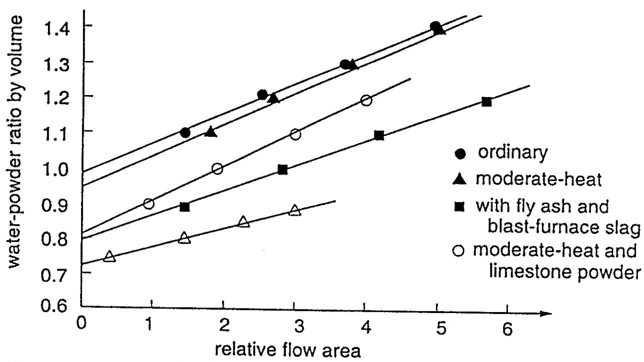

Fig.8 Relationship between the relative flow area and water-powder ratios in cement paste

4.2 Aggregate

Aggregate is the durable and strong ingredient in concrete. In general, higher the aggregate content of the concrete, the better the quality of the hardened concrete. However, it has been revealed by Yoshida Tokujiro that this is not always the case. In fact, it is preferable that the ratio of cement, fine aggregate, and coarse aggregate be 1:1:2 in practice to obtain the maximum strength using a particular set of materials. If the aggregate volume exceeds this ratio, the attainable maximum strength falls drastically[11] (see Fig. 9).

Yoshida also illustrates in his report that when the ratio of cement to fine aggregate by volume is set at 1:1.5, a ratio of cement to coarse aggregate by volume greater than 1: 1.5 leads to drastic losses in maximum attainable strength. Careful and thorough consolidation was conducted in Yoshida's study. Water is extracted under pressure from the concrete after placement in the formwork until the water-cement ratio is reduced to approximately 22% by weight. Yoshida states that the optimum water-cement ratio by weight before placing is 31% for maximum strength development. We were astounded recently to find that the proportions 1:1.5:1.5 by volume happen to be equivalent to the proportioning required for self-compacting concrete using the same materials (see Fig. 10).

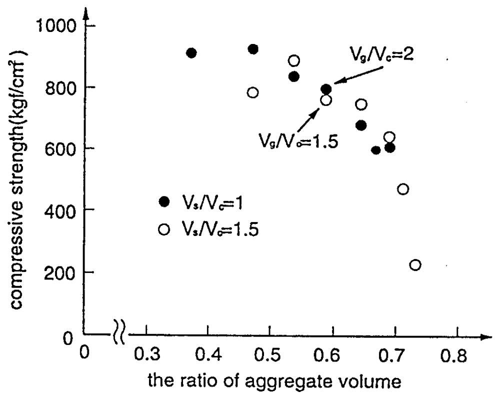

Fig.9 Variation of compressive strength with respect to the ratio of aggregate volume

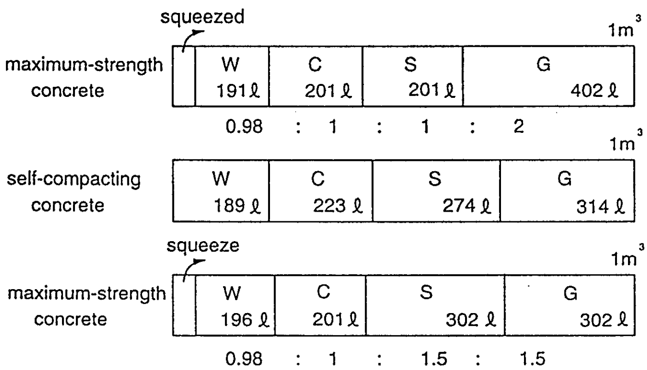

Fig.10 Mixtures of self-compacting concrete with superplasticizer and maximum-strength concrete without superplasticizer

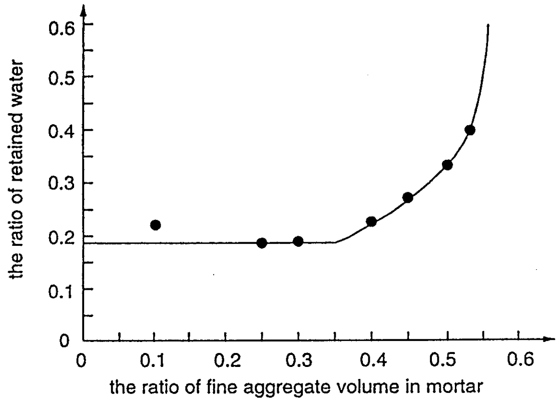

Fig.11 Relationship between the ratio of retained water and the ratio of fine aggregate

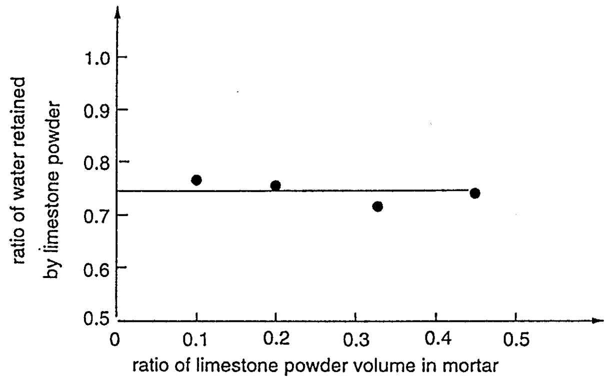

Fig.12 The ratio of retained water by limestone powder

The larger the proportion of coarse aggregate with large grain diameters, the better the mechanical properties of the hardened concrete, assuming the total amount of aggregate is the same. Yoshida recommends in his report a ratio of fine aggregate to coarse aggregate ratio of 1:2 by volume. From the standpoint of the capability of fresh concrete to pass through spaces between obstacles, however, it is preferable to increase the proportion of fine aggregate. In the case of self-compacting concrete, a ratio of fine aggregate to coarse aggregate of approximately 1:1 by volume is recommended for practical purposes. In this light, it is inferred that the present self-compacting concrete is synonymous with the maximum-strength concrete mixture with a ratio of fine aggregate to coarse aggregate of 1:1 maintained by Yoshida, to which a superplasticizer is added to increase deformability up to the level at which self-compactability is attained. In other words, the uniform extraction of water by applying pressure implies that the concrete is required to contain sufficient paste to avoid direct contact between aggregate particles.

The authors have attempted to quantitatively investigate the effects of fine aggregate on mortar flow, and have reached a provisional conclusion. According to this work, the amount of water confined by fine aggregate particles is almost proportional to the volume of the fine aggregate, as long as the volume of fine aggregate is within certain limits. The proportion is practically constant at approximately 20% [12] (see Fig. 11). This value is about one fifth of the ratio of water confined by powders. It has also been revealed that the fine grains of fine aggregate in fresh concrete or mortar should rather be regarded as powder. According to our findings, so far, it is appropriate to regard particles smaller than 90 μm as powder and those larger than 90μm as fine aggregate.

Apart from the difference in water confinement ratio, fine aggregate is distinguished from powder by its property of exhibiting an apparent drastic increase in the ratio of confined water after it has exceeded a certain limit (see Fig. 11). This phenomenon is not observed with powders. Limestone powder was assumed to be fine aggregate, and the relationship between the ratio of the limestone powder in mortar and the ratio of water confined by the powder was determined. As a result, the ratio of water confined by the powder was found to be constant (see Fig. 12). The sudden increase in the ratio of water confined by fine aggregate is considered to be due to the increase in the opportunity for direct contact between fine aggregate particles, which leads to an increase in the opportunity for interlocking.

Coarse aggregate particles are considered to confine practically no water. When their volume in the concrete exceeds a certain limit, the opportunity for direct contact between them drastically increases, resulting in increased interlocking to an extent more intense than in the case of fine aggregate.

4.3 Water and superplasticizer

The main role of water in fresh concrete is to impart sufficient deformability on the concrete. If the amount of free water is defined as the amount of water in the paste minus the amount confined by powders and fine aggregate, the flow area of the paste and the flow area of mortar with a constant fine aggregate content are proportional to the amount of free water (see Fig. 13). Also, the viscosity of the paste decreases as the volumetric ratio of free water to powder increases. It has also been revealed that the funnel velocity of paste and mortar is proportional to the ratio of free water to powder by volume[13] (see Fig. 14).

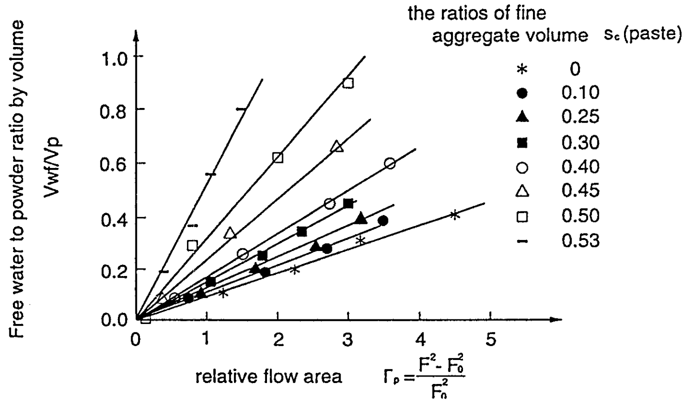

Fig.13 Relationship between free water to powder ratio and relative flow area

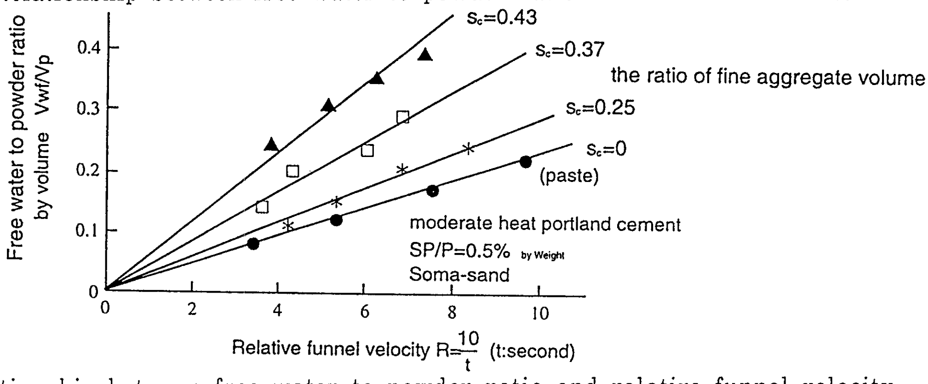

Fig.14 Relationship between free water to powder ratio and relative funnel velocity

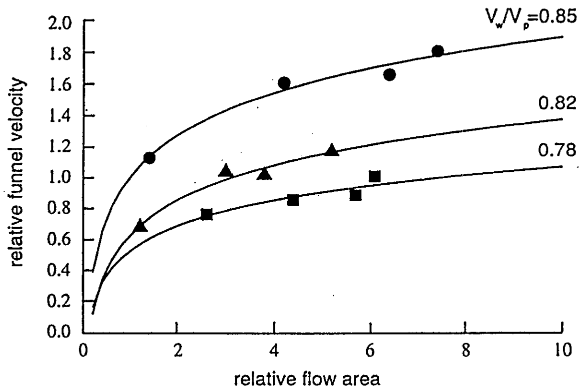

Fig.15 Relationship between relative flow area and relative funnel velocity

Superplasticizers also increase the deformability of concrete in a way similar to water. Where the dosage of a superplasticizer is small, the flow area as well as the funnel velocity increase as the dosage increases. At the dosages normally used for self-compacting concrete, however, large changes in flow area are associated with only relatively small changes in the funnel velocity. This is a distinctive characteristic on exhibited by water (see Fig. 15). Another difference is that superplasticizers can increase the deformability without increasing the amount of bleed water. This is one of the key properties that makes superplasticizers essential for self-compacting concrete. Self-compacting concrete would have been impossible without the development of superplasticizers. It is necessary to suitably establish the water-powder ratio and the dosage of the superplasticizer, in order to suitably balance the deformability and the resistance to segregation required for self-compacting concrete.

The defect of superplasticizers is that their effects are significantly dependent not only on the combinations of powders but also on the temperature and mixing methods. From the standpoint of production control of self-compacting concrete, the superplasticizer is required to be insensitive, to a certain extent, to conditions such as dosage and temperature, mixing conditions, and changes in time after mixing. Development of such a superplasticizer is strongly demanded.

4.4 Viscosity agent or segregation-inhibiting agent

A viscosity agent or segregation-inhibiting agent is used to increase the viscosity of the paste and to increase resistance to segregation. Viscosity agents consisting of water-soluble polymers like cellulose are thought to change the viscosity of water in concrete. Those consisting of polymers insoluble in water, like polysaccharides, are thought to absorb water and swell, confining the water in concrete in a way similar to the powder. This reduces the amount of free water, thereby increasing viscosity[14].

Segregation-inhibiting agents are being utilized as a means to maximize deformability within limits and simultaneously maintain suitable resistance to segregation. This makes possible the realization of self-compacting concrete that is capable of adapting to a wide range of production scatter, particularly in water content. Segregation-inhibiting agents have now become some what redundant in self-compacting concrete, as methods of mix design that produce similar effects without using them have recently been proposed. It is appropriate to use these agents as required, however, because the powder content can be reduced by their use.

4.5 Air

Air bubbles entrained into the concrete by air-entraining agents are necessary for increasing the freezing and thawing resistance of hardened concrete. In fresh concrete, air bubbles confine a marginal amount of water on their surfaces. In that sense, air bubbles can be regarded as an ingredient with a marginal water confinement ratio. Since air bubbles are not capable of supporting aggregate particles as powders are, entrainment of air bubbles seems to have little effect on preventing contact between aggregate particles. Thus air bubbles can simply be regarded as a filler in the mix design of self-compacting concrete.

5. METHOD OF MIX DESIGN

5.1 Volume of coarse aggregate

When the volume of coarse aggregate in concrete exceeds a certain limit, the opportunities for contact between coarse aggregate particles drastically increase, causing interlocking, and increasing the possibility of blockage on passing th-rough spaces between steel bars. Therefore, the first point to be considered when designing self-compacting concrete is holding the volume of coarse aggregate below this limit.

According to the information obtained, this limit is more closely related to the percentage of solid material than to the volume of coarse aggregate as such. It has also been revealed that the limit is in the range of solid content between 50% and 60%. It is also known that the possibility of such interlocking is negligible if the solid content of coarse aggregate is lower than 50% and if adequate mortar is used (see Fig. 16). This implies that the volume of coarse aggregate can be increased if well-graded and well-shaped aggregate is used. Use of river gravel generally permits a large coarse aggregate volume. The limit seems to vary slightly depending on the properties of the mortar, particularly those of the powder. This will be elucidated by future study.

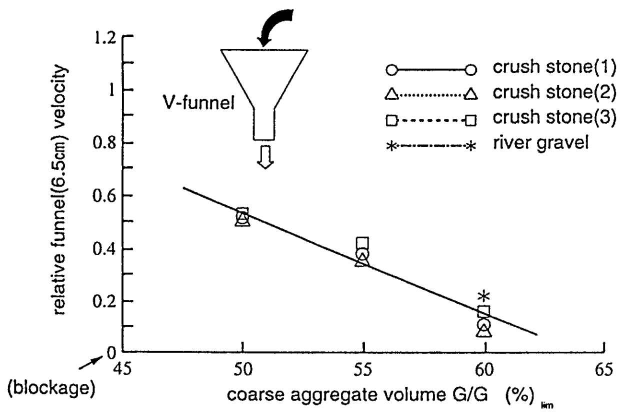

Fig.16 Relationship between content of coarse aggregate and relative funnel velocity

5.2 Volume of fine aggregate

The volume of fine aggregate in mortar is important as in the case of coarse aggregate. Conversely, however, the volume of fine aggregate itself is found to be more important than its solid volume, though the reason for this has not been elucidated. This should also be a future subject of study.

If a suitable paste is used and the volume of fine aggregate is below a certain limit, self-compacting concrete is obtained with no appreciable direct interlocking of fine aggregate particles. This limit seems to be independent of the type of fine aggregate, but seems to depend on the properties of the paste. The relationship between the optimum volume of fine aggregate and the properties of the paste will be investigated in the future.

We have demonstrated that self-compacting concrete can safely be produced if particles larger than 90 μm are assumed to be coarse-grain fine aggregate and those smaller than this are assumed to be powder, and if the volume of coarse-grain fine aggregate is set at 40% of the volume of mortar.

5.3 Volumetric water-powder ratio and dosage of superplasticizer

When the volume of fine aggregate has been specified, the volumetric water-powder ratio and the dosage of the superplasticizer must then be determined. High water-powder ratio not only causes segregation of water, but also causes excessive reduction of paste viscosity, resulting in segregation of the coarse aggregate. Conversely, low water-powder ratio leads to high viscosity impairing the ability of the concrete to pass through small spaces. This is also the case when a superplasticizer is used. However, general methods have not yet been established for determining the water-powder ratio and the dosage of superplasticizer so as to impart suitable deformability and viscosity on the paste or mortar. This is a major subject for the future from the standpoint of establishing a method of mix design.

5.4 Mix design system

There are numerous solutions for the mix proportion, which realize self-compactability. By specifying some of the materials or proportions, the optimum proportions are fixed within a certain range. In other words, a variety of proportions are obtained depending on what is specified first. The proportions currently used may not necessarily be the optimum obtainable from the combination of materials, but rather may simply be one of the many possibilities which realize self-compactability.

Assuming normal supply from a ready-mixed concrete plant, a mix design system for self-compacting general-purpose high-performance concrete has been proposed[3] (see Fig. 17). This is a limited system premised on the use of moderate heat portland cement or cement with a high belite content. Assuming application to structures in general, it is appropriate at present to use these cements, in consideration not only of the properties of fresh concrete, such as the ratio of confined water, but also the properties of green and hardened concrete, such as heat generation, strength development, drying shrinkage, and carbonation.

This is a system whereby the quality of the hardened concrete is normally automatically ensured if the concrete attains self-compactability while fresh. The mix design is simplified and its reliability is increased by limiting the range of cement quality. In addition, the superplasticizers used in combination with these cements may see rapid improvement when sizable data has been accumulated. Thus, putting limits on the quality of the powder (cement) to be used is of great significance.

The target deformability and resistance to segregation are specified at a high degree of self-compactability. Self-compactability is therefore ensured for general use. The degree of self-compactability may become discretionary when the reliability of quality control technology has been increased and the relationship between filling properties in real structures and the characteristics of the concrete has been quantitatively elucidated.

In the proposed mix design system, the amounts of coarse and fine aggregates are specified on the safe side. A method of determining the amount of coarse aggregate amount in the concrete or the amount of fine aggregate in the mortar with respect to specific material properties is indicated in this system, thus making it adaptable to various types of coarse aggregate, as well as to fluctuations during production.

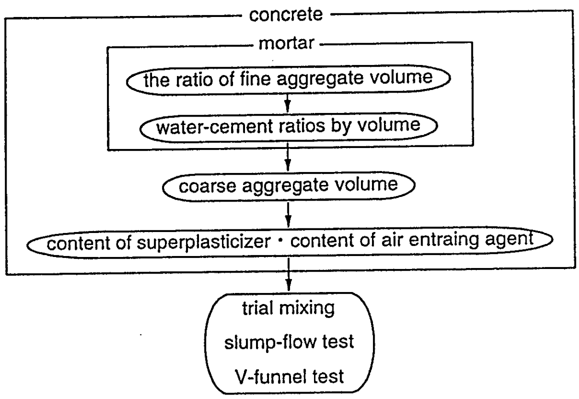

Fig.17 Mix design system for self-compacting general-purpose high-performance concrete

Methods of increasing the aggregate content may be proposed in the future, when a quantitative evaluation of the effects of the interference between fine and coarse aggregate particles has been made and production quality control technology has improved. In the present system, the water-powder ratio and the dosage of superplasticizer are not determined until the mortar or concrete is actually mixed. The major reason for this is that the effects of mixing are difficult to deal with quantitatively. If the effects of the superplasticizer and other conditions could be evaluated before actual mixing, there would be a possibility of designing concrete without trial mixing. Future studies will be directed toward the development of an analytical method whereby the behavior of fresh concrete can be sequentially predicted from the materials, proportioning, methods of production, and environmental conditions.

5.5 Method of evaluating degree of self-compactability

The establishment of a method for quantitatively evaluating the degree of self-compactability is a key issue in establishing the mix design system. In the system currently proposed, the slump flow test and V-funnel test are utilized as the means of evaluation. Evaluation by these tests is applicable only to cases within the range of materials and proportioning proposed here. It is unknown whether evaluation by these two tests alone is valid for concretes of arbitrary materials and proportioning. The boundary conditions actually met at the site of placement may vary, widely and there may be a number of factors affecting self-compactability. It is therefore impracticable to express the properties of concrete with only two test values (though this is much better than one). Improvement in techniques for analytically predicting the behavior of fresh concrete is there fore required, as well as the accumulation of data linking the results of these evaluations to the self-compacting properties obtained by actual placing into real structures.

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